Open-Loop Performance of COBALT Precision Landing Payload on a Commercial Sub-Orbital Rocket

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An open-loop flight test campaign of the NASA COBALT (CoOperative Blending of Autonomous Landing Technologies) platform was conducted onboard the Masten Xodiac suborbital rocket testbed. The COBALT platform integrates NASA Guidance, Navigation and Control (GN&C) sensing technologies for autonomous, precise soft landing, including the Navigation Doppler Lidar (NDL) velocity and range sensor and the Lander Vision System (LVS) Terrain Relative Navigation (TRN) system. A specialized navigation filter running onboard COBALT fuses the NDL and LVS data in real time to produce a navigation solution that is independent of GPS and suitable for future, autonomous, planetary, landing systems. COBALT was a passive payload during the open loop tests. COBALT's sensors were actively taking data and processing it in real time, but the Xodiac rocket flew with its own GPS-navigation system as a risk reduction activity in the maturation of the technologies towards spaceflight. A future closed-loop test campaign is planned where the COBALT navigation solution will be used to fly its host vehicle.

I. Introduction

Future NASA missions, whether they are robotic or human, will have a need for Precision Landing and Hazard Avoidance (PL&HA) technologies. The PL&HA domain focus is the development, integration, testing and spaceflight infusion of GN&C functions that are critical to the safety and success of future lander missions, but they also have direct applications to other mission phases such as proximity operations and rendezvous and docking. The COBALT project[1],[2] which falls under this domain, was a two year project that focused on a subset of these technologies: Terrain Relative Navigation, a Navigation Doppler Lidar Velocimeter, and the improvement of navigation algorithms that blend together IMU rate measurements, TRN images for position updates, and precise NDL velocity measurements for a completely autonomous onboard navigation system. These technologies were successfully tested onboard the Masten Space Systems (MSS) Xodiac suborbital rocket during three ground tethered tests and two free flights during the spring of 2017.

Prior to the flights, the NASA and MSS teams conducted ground tests at the Xodiac hangar to verify and revise software and data interfaces on both the payload and vehicle, and rehearsed and matured operational

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procedures. The three tether tests were conducted at the launch pad with the vehicle tethered to a crane, which minimizes the risk of vehicle/payload loss in the event of an unanticipated flight anomaly. The two free flights were conducted after joint team assessments of tether performance and concurrence on flight readiness.

The nominal trajectory for the two free flights included a maximum 500-meter altitude, 25-meters/second velocity, and 300-meter down range divert to a targeted landing pad as shown in figure 1. These flights provided the first physical tests capable of simultaneously generating synchronous and dynamically-consistent IMU, TRN and NDL measurements for processing within the COBALT navigation filter. Valuable data was obtained from both flights: some indicating good performance but some revealing new challenges.

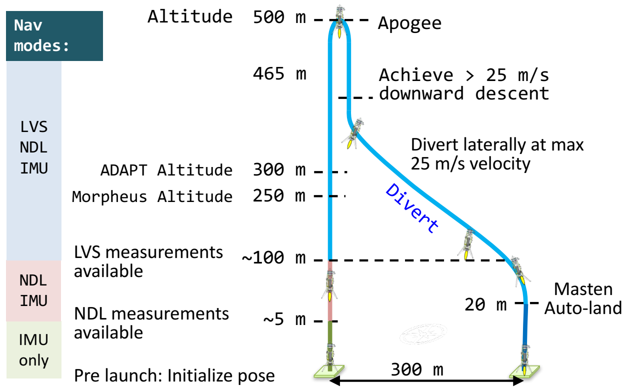

Figure 1. COBALT FLight Test ConOps

II. COBALT Platfrom Overview

The COBALT payload shown on the left of figure 2, consists of the following main components:

- Generation 3 Navigation Doppler Lidar for velocity and range measurements and its dedicated FPGA and processor.[3]
- The Lander Vision System for TRN for providing position estimates, which consists of an optical camera and an LN-200 IMUm[4]
- A custom compute element with its own stand alone power unit
- A cylindrical frame to mate the payload onto the MSS Xodiac vehicle

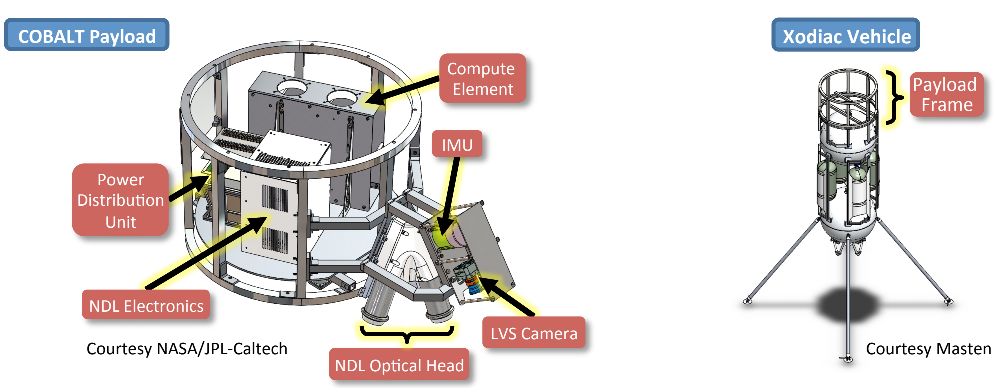

Figure 2. CAD models of COBALT payload (left) and Xodiac vehicle (right).

The image on the right of figure 2 is a model of the Xodiac vehicle with the mounted COBALT payload frame. Figure 3 shows photos of the payload frame and sensor assembly as flown during the open loop campaign.

Figure 3. Images of the fully-integrated COBALT payload hardware

III. Analysis of COBALT Flight Performance

This section is an overview of the COBALT navigation filter performance and data analysis of the second free flight. The test data from the first free flight revealed an unanticipated challenge with COBALT's main flight processor that resulted in data logging errors, some IMU data loss, and a significantly reduced number of LVS images. A primary objective of this open-loop campaign was the collection of a rich data set from IMU, NDL and TRN for informing subsequent navigation filter and other code revisions within both COBALT and Xodiac in preparation for the future closed-loop campaign. Changing a few software parameters for the second free flight, enabled collection of a complete data set (IMU, NDL and TRN) and fulfillment of the primary campaign objective, but resulted in NDL data being re-processed after flight, rather than real-time processed in the navigation filter.

Therefore, the results in this paper are divided into two parts: as-flown navigation filter solution with IMU and TRN measurements, and post-processed navigation filter solution with IMU, TRN, and high frequency NDL velocity measurements. Additionally, independent truth telemetry was not available with the flight tests, so the comparison plots are not error plots, but rather difference plots between two independent navigation solutions.

A. As-Flown COBALT Navigation (IMU + TRN)

In general, the LVS TRN system performed well during the flights where the collected images provided good matches with features from the onboard reconnaissance maps of the Mojave region. NDL measurement data also indicated excellent overall sensor performance within the intended flight regime of propulsive descent. Some measurement outliers were observed during takeoff and landing, which are regions that fall outside of the intended regime. Plume-induced interference was also observed with in some of the NDL measurement data following vehicle pitch-over at peak altitude. However, this phenomenon would not be present when landing on the Moon or other airless bodies and is not expected to be an issue on Mars or in other thin atmospheres.

Figure 4 shows the position differences between the COBALT (IMU+TRN) navigation configuration and Xodiac GPS-based navigation during the second flight with coordinates in a local East-North-Up (ENU) frame. The first processed TRN image occurs at around 20 seconds and it updates the position by approximately 4 meters, with much smaller position updates from subsequent images.

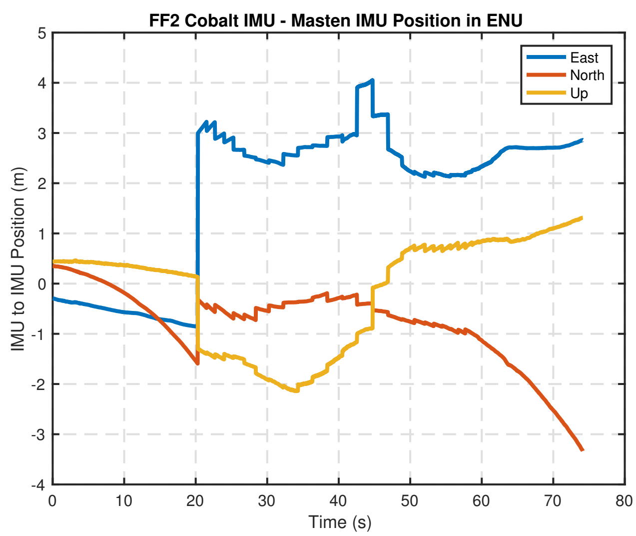

Figure 4. FF2 COBALT IMU and Xodiac IMU Position Difference

The initial offset between the COBALT IMU and the Xodiac IMU positions that can be seen on figure 4 is expected since these were fixed on the rocket at approximately 50cm apart. The two to four meter offsets seen at the end of the flight could be, in part, due to the difference in geodetic altitude between the launch and landing pads. The Xodiac vehicle captured the differences with their GPS-based navigation. However, the COBALT team is still assessing whether or not the terrain model used for its NDL range measurements captured the slope of the terrain with enough fidelity. As part of this analysis, figures 5 and 6 show the position of relevant points for both COBALT and Xodiac over the launch and landing pads. Figure 5 shows that the MSS team considers the location of the GPS antenna equivalent to the location of the navigation center at the Xodiac IMU. In reality, these two points are fixed in the rocket at approximately 76cm apart, and the Xodiac data for the location of the GPS antenna and IMU throughout the flight are within a few cm of each other. The COBALT - Xodiac data comparisons use the IMU point and not the antenna location, but the team is still investigating whether or not this could be a source or small systematic errors.

Figure 6 shows that, at landing, COBALT lands at about 5.5 meters above the pad, but it was physically located at about 2.5 meters above the ground, closer to where the Xodiac IMU point is located. The launch pad altitude is shown above the landing pad center as a reference, to emphasize the slope of the terrain between the pads.

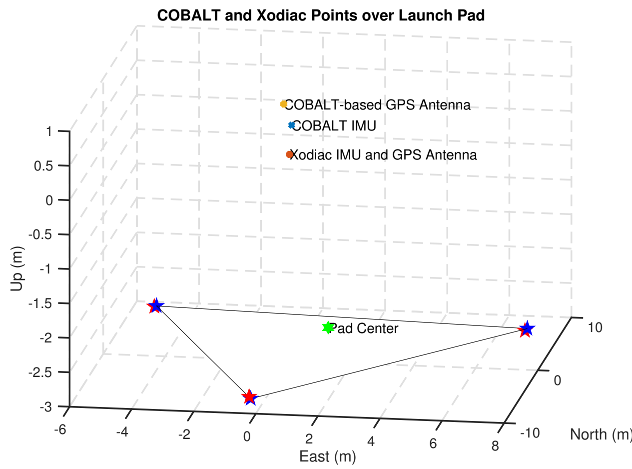

Figure 5. COBALT and Xodiac Points at the Launch Pad

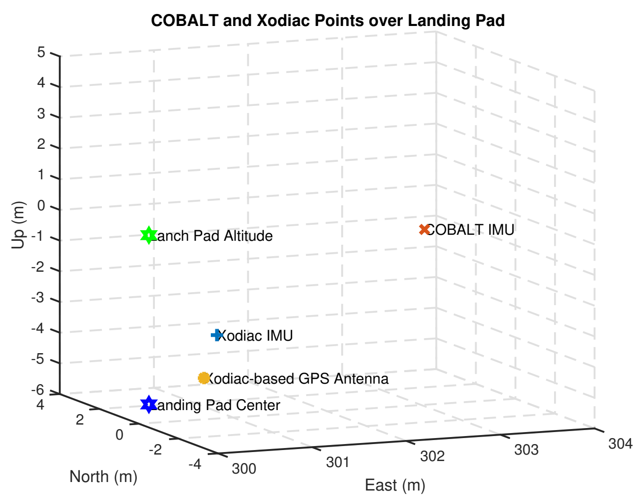

Figure 6. COBALT and Xodiac Points at the Landing Pad

Figure 7 shows the difference in velocity at each of the IMUs. As previously mentioned, during flight, the NDL was taking measurements near the ground and this caused a few outlier measurements in velocity at take-off and landing. Once that was corrected in the post-flight reprocessed data, the velocity measurements improve as seen in figure 9 described in the next subsection.

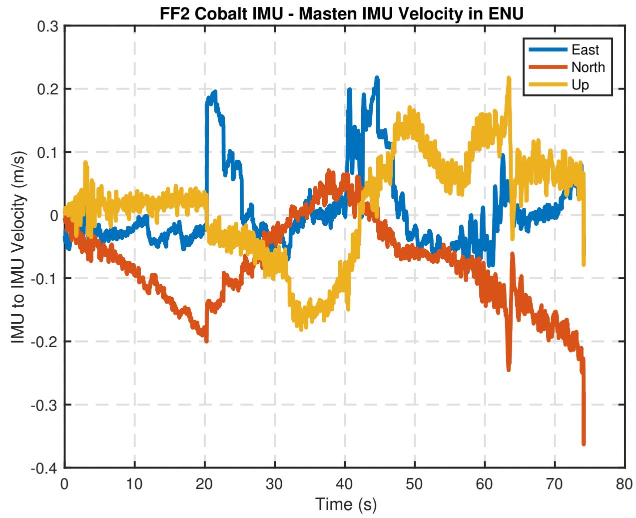

Figure 7. FF2 COBALT IMU and Xodiac IMU Velocity Difference

B. Post-Processed COBALT Navigation (IMU + TRN + NDL)

The data for this section was post-processed after flight. In addition to incorporating the NDL velocity measurements, the decision was made to incorporate those measurements only above a 10m altitude threshold to prevent outliers near the ground during take off and landing that were seen during the flights.

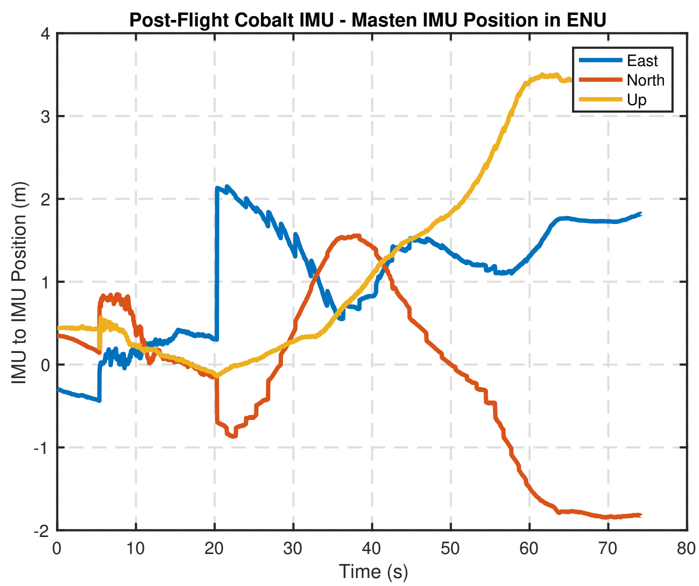

Figure 8. Post Flight COBALT IMU and Xodiac IMU Position Difference

Similar to figure 4, the step in position difference at approximately 20 seconds occurs at the first TRN measurement update in figure 8 as map relative localization data becomes available. Again, this step is anticipated, reflecting a correction to the filter state that compensates for IMU propagation errors that have accumulated since launch. Following this period of the flight, processing the NDL data appears to

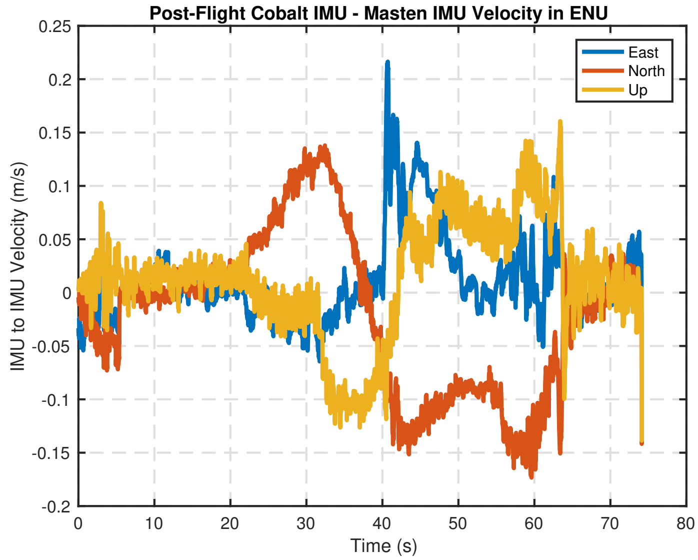

Figure 9. Post Flight COBALT IMU and Xodiac IMU Velocity Difference

reduce the differences between COBALT and Xodiac navigation, in comparison to the as-flown (IMU+TRN) comparison.

The near constant position error in the last 10 seconds of flight is similar to the one shown in figure 7 and likely due to the systematic position errors that are being investigated. However, figure 9 is an improvement over figure 7 because the overall error in velocity is reduced at take off and landing when NDL velocity data is processed by the navigation filter.

IV. Conclusions

The open-loop campaign accomplished the objectives planned for the ground, tether, and free flights. The NDL sensor generated excellent data operating under a dynamically relevant environment, and the navigation solution improved when velocity data was incorporated. However, the campaign had some challenges and both the NASA and MSS teams are currently assessing the requirements for the next generation COBALT payload as well as refinements to ground tests, including using the same GPS survey locations on the ground to make data comparisons more straightforward in future flight campaigns.

Acknowledgments

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